The Gradual Expansion Muscle Flap

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Summary: High energy open fractures of the tibia have traditionally been fraught with challenges to include bone comminution or loss, soft tissue loss, nonunion, and infection. A number of techniques have been implemented to treat the severe soft tissue loss typically involving the anteromedial surface of the tibia to include wet to dry dressings or Papineau techniques, negative pressure wound therapy, acellular dermal matrices, and rotational or free tissue transfer with Masquelet technique, primary shortening, and distraction osteogenesis to address bone loss. We present a novel technique and subsequent case series that obviates the need of free tissue transfer while treating high energy type IIIB open tibia fractures by performing an acute shortening and angulation of the tibia and rotational muscle flap coverage and split thickness skin grafting of the soft tissue defect. Distraction histiogenesis with circular external fixation is then used to correct the residual osseous deformity while stretching the rotational muscle flap.

Key Words: shortening and angulation, Taylor Spatial Frame, III B tibia fracture, flap coverage

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INTRODUCTION

High-energy open fractures of the tibia are challenging injuries to treat due to their propensity for nonunion, increased incidence of deep infection, and the common need for soft tissue coverage.[1–7] Because the anteromedial surface of the tibial shaft is subcutaneous along nearly its entire length, commonly encountered traumatic wounds frequently require rotational muscle coverage or free tissue transfer to obtain closure. Although coverage of smaller defects can usually be obtained with a rotational flap, larger size defects commonly require free tissue transfer. A number of techniques have historically been used to cover large soft tissue defects when free tissue transfer is not an option. Traditional wet-to-dry dressing changes (ie, Papineau technique)[8] and negative pressure wound therapy have been shown to promote a layer of granulation tissue that is amenable to split-thickness skin grafting or eventual wound healing by secondary intention.[9,10] The use of acellular dermal matrices (ie, Integra; Integra Lifesciences, Plainsboro, NJ) has recently gained popularity as an adjunctive wound treatment due to its ability to generate tissue neovascularization over exposed bone that is also amenable to split-thickness skin grafting after tissue incorporation.[11] In addition to donor site morbidity, free tissue transfer is dependent on the availability and expertise of a qualified microvascular surgeon; the presence of a single vessel limb may preclude the safe use of free tissue transfer due to microvascular steal syndrome and the potential for catastrophic limb demise.[12,13]

The high-energy nature of type III open tibia fractures also predisposes to bone loss, another challenge in the management of these injuries. Multiple surgical options are available for the management of bone loss, including staged bone grafting within an induced membrane (Masquelet technique), primary shortening of small defects, or distraction osteogenesis using the methods of Ilizarov.[1,2,14–17] Multiple Ilizarov techniques have been described for the management of composite bone and soft tissue loss, including the combined use of distraction osteogenesis and free tissue transfer for reconstruction of massive composite defects.[18–20] Shortening and angulation has also been described and reported as a means of avoiding the need for soft tissue coverage when free tissue transfer is not feasible.[21,22]

Because limb salvage situations occur in which rotational muscle coverage is inadequate and free flap coverage is less desirable, we use the Gradual Expansion Muscle (GEM) flap to obtain wound coverage and avoid amputation of these massive soft tissue injuries. By combining acute shortening and angulation with local rotational flaps, and harnessing the power of distraction histiogenesis, rotational coverage can be expanded to larger defects which previously would have required free tissue transfer.

Surgical Technique

The GEM flap for large soft tissue defects of the leg requires a 2-stage approach. In the first stage, acute shortening and angulation of the extremity is combined with rotational muscle coverage to obtain the necessary soft tissue coverage. In the second stage, after the flap has adequately set and overlying skin graft has full adherence, a Taylor Spatial Frame (Smith and Nephew, Memphis, TN) is applied to afford a gradual correction of the induced deformity by stretching the flap, which is centered within the concavity of the deformity.

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First Stage

The patient is positioned on a radiolucent table that allows complete access to the extremity. No tourniquet is used, and the thigh should be shaved and prepped into the field for harvesting of skin graft. In our practice, a spanning unilateral external fixator has almost always been applied at the time of the index wound debridement for traumatic injuries. Because an intraoperative fixator adjustment will be required and the frame must be prepped into the field, every effort should be given to ensuring sterility of the frame during prepping. We typically prep the frame with 10% povidone–iodine solution (Betadine; Purdue Pharmaceuticals, Stamford, CT) and sequester the fixator and pin sites with towels to prevent wound contamination until the intraoperative adjustments are made; however, no strong empiric evidence currently exists to recommend any 1 management strategy for the fixator. After a thorough wound debridement and irrigation has been performed and it is determined that the wound is amenable to soft tissue coverage, the appropriately selected muscle belly is mobilized, rotated, and set into place using standard flap techniques. If any residual soft tissue defect remains, it will be closed using acute shortening and angulation.

The fixator is loosened, allowing complete control of the fracture. Because large wounds are nearly always anterior and medial, the typical induced deformity necessary is recurvatum and varus angulation (Figs. 1A–E). Although the limb can successfully be shortened and angulated even in the setting of isolated soft tissue loss by bayoneting the bone segments, a bone defect is frequently present and typically is much easier to manage when creating an induced deformity. Before creation of the induced deformity, baseline intraoperative Doppler testing should be done to assess for triphasic pulse signals distally at the remaining arterial sources. The deformity is then induced slowly until the soft tissue

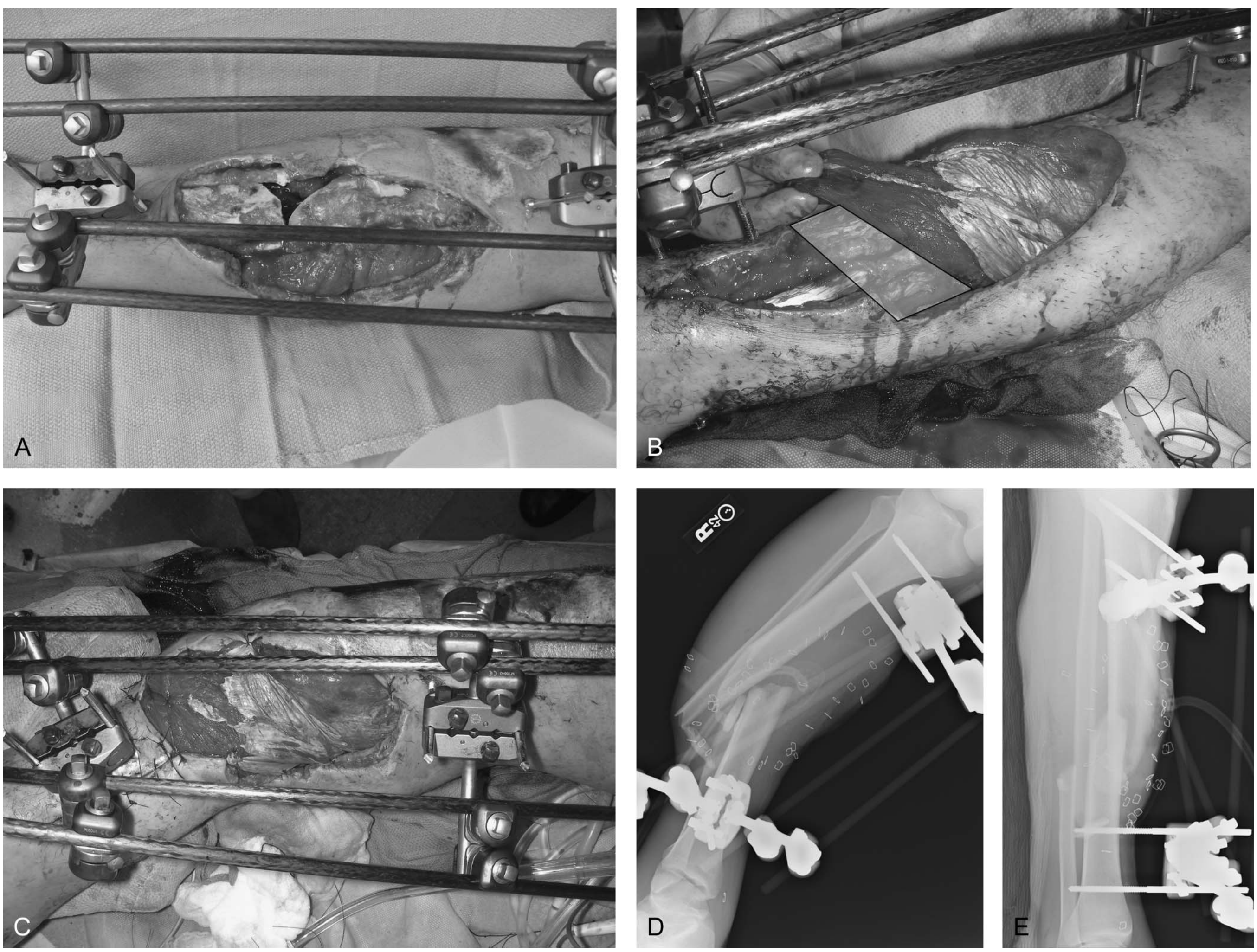

FIGURE 1. A, 22-year-old patient injured after his Humvee struck an improvised explosive device, sustaining a III-B open tibia fracture with large anteromedial soft tissue defect and bone loss involving the middle third of the leg. B, After maximal soleus rotational coverage, large area of distal wound remains open (shaded area) measuring approximately 25 cm^2. C, Shortening and angulation closes the gap, with the distal fasciotomy incision closed primarily. Varus alone was required to close the wound. D, E, AP and lateral radiographs at time of acute shortening with angulation.

FIGURE 2. A, III-B tibia fracture before GEM flap with a contralateral transtibial amputation. B C, AP and lateral view of the injured extremity after acute shortening and angulation, GEM flap coverage, skin grafting, and circular external fixator application. D E, AP and lateral radiographs after initial shortening and angulation with GEM flap coverage. F G, Final AP and lateral radiographs after circular external fixator removal. Note the correction of the initial varus and recurvatum deformities.

defect remaining is closed and allows for primary skin closure and/or split-thickness skin grafting. Repeat Doppler examination should confirm persistence in the quality of triphasic pulse signals. If any concern exists for vascular compromise, further induced rotational deformity may allow return of signals without compromising the wound closure; failure to return Doppler signals indicates a need to reduce the amount of acute shortening or angulation. Although previous authors have suggested a threshold of 3 cm of acute shortening to prevent vascular compromise, we have routinely shortened well beyond 3 cm, even to 8 cm, without vascular compromise, relying on intraoperative Doppler signals as a guide.[18,22]

With the necessary soft tissue coverage obtained, the fixator is retightened in the newly adjusted position and reprepped with on-field Betadine to prevent wound contamination with newly exposed bacteria.[23] Skin grafting and approximation of skin edges are then performed to complete the soft tissue reconstruction. We liberally apply negative pressure wound therapy (Wound Vac; Kinetic Concepts, Inc., San Antonio, TX) for the management of the skin graft sites and incisions, using the Wound Vac over skin graft sites for 5 days and over incisions for 48–72 hours to improve skin graft adherence.[24,25] Because the rotated muscle flap and skin graft lies within the concavity of the induced deformity, sufficient healing time is allowed to ensure graft adherence and neovascularization into the flap before staged bony reconstruction—generally within 3 weeks.

Second Stage

When the soft tissue envelope has healed at approximately 10–21 days after wound coverage, the patient returns to the operative room for removal of the unilateral external fixator and placement of a Taylor Spatial Frame (Figs. 2A–G). Because most of these injuries are complicated by composite bone and soft tissue loss, distraction osteogenesis at a distal site is also required to restore limb length. For fractures of the diaphysis or distal tibia, the corticotomy is made within the proximal metaphysis. Every effort should be made to avoid the diaphysis and perform a metaphyseal corticotomy, where regenerate formation is more reliable and maturation occurs more quickly. In instances of massive bone loss, tandem corticotomies and multiple transport segments may be chosen to reduce the overall time in the fixator. For proximal tibia fractures, a distal corticotomy is selected.[26]

We prefer to use a 2/3 ring proximally on the tibia and full rings distally, that allows for unrestricted knee flexion. We also prefer to employ a hybrid technique, using a combination of tensioned thin wires and hydroxyapatite-coated 6 mm half pins in each bone segment. Rings are mounted orthogonal to their respective bone segments, and in situations where a short bony segment is encountered, precluding the use of multiple half pins, multiple tensioned thin wires can be used per segment, providing adequate rigid fixation as originally described and taught by Ilizarov.[16,17] Fast-fix struts (Smith and Nephew) are then applied to the frame with the induced deformity uncorrected, completing the frame construct. Additional rings are applied as necessary to allow for distraction osteogenesis of any corticotomies and restoration of limb length.

We prefer to begin the gradual deformity correction immediately, without a latency period. The power and utility of the Taylor Spatial Frame lies in the ability to perform gradual software-driven deformity corrections (Taylor Spatial Frame Software, version 3.0.1; Smith and Nephew) based on simple orthogonal radiographs. The concave skin edge adjacent to the muscle flap is defined as the “Structure at Risk,” and distraction here is limited to 1 mm per day. The induced deformity correction can be fine tuned at subsequent office visits to allow correct restoration of limb rotation, length, and angular alignment over time. The “Total Residual” software program makes these subsequent corrections simple. We allow immediate weight bearing as tolerated in the circular fixator, even when shortening and angulation remain present. Custom frame foot plates can be fabricated and added to the frame to allow easier weight bearing in the setting of limb shortening.[27] Routine autogenous bone grafting and/or use of recombinant bone morphogenic proteins are not typically done unless concerns arise regarding fracture healing. We prefer to augment regenerate maturation with the use of low-intensity pulsed ultrasound (Exogen; Smith and Nephew).[28]

CLINICAL SERIES

Between May 2008 and June 2011, we treated 5 patients with composite bone and soft tissue loss of the tibia using the GEM flap technique. The average age was 26.0 years (range, 21–39 years), and all patients were male. Four patients had sustained their injuries as a result of blast mechanisms during US combat operations, and another as the result of a crush injury. All 5 patients had anteromedial soft tissue defects too large for rotational flap coverage or closure with acute shortening and angulation alone, and each was deemed a poor candidate for or declined free tissue transfer. The average soft tissue defect was 167 cm^2 (range, 48–306 cm^2), and the average bone loss measured 7.80 cm (range, 1–17 cm). Three of the 5 patients had a contralateral traumatic limb amputation. The average follow-up was 23.6 months (range, 15–39 months).

A soleus or hemisoleus flap was used in 2 patients and a medial gastrocnemius flap in 4. One of the patients, with a soft tissue defect measuring 30 × 8 cm, required the use of both a hemisoleus and medial gastrocnemius flap. All flaps were covered with split-thickness skin grafting and demonstrated nearly 100% adherence after negative pressure wound therapy removal on postoperative day 5.

Acute shortening averaged 5.2 cm (range, 3–6 cm) while angulation averaged 30.4 degrees (range, 16–45 degrees) of varus and 20.6 degrees (range 0–40 degrees) of recurvatum. Four patients required a corticotomy and distraction osteogenesis to obtain lost bone stock and regain limb length, including 1 patient who underwent tandem transport with 3 distal corticotomies. The average latency time between stages 1 and 2 was 16 days (range, 7–21 days) with the deformity corrections averaging 52.2 days (range, 26–77 days). Objective clinical data for 1 patient were available that demonstrated longitudinal flap lengthening of 13.7% (2.1 cm) at the immediate completion of deformity correction.

There were no wound or flap complications in the 5 patients, and no deep infections occurred. All fractures and regenerate bone ultimately healed 1 patient required autogenous bone grafting of his defect after becoming noncompliant with distraction osteogenesis at the completion of his deformity correction and being lost to follow-up for 2 months. This was performed directly through his GEM flap 8 months after his index surgeries without development of flap or wound complications. One other patient with premature fibular consolidation required revision osteotomy and frame adjustment before completion of realignment. This patient ultimately chose to undergo amputation of his salvaged limb due to dissatisfaction with his current functional outcome and chronic distal tibia osteomyelitis (distal to his GEM flap) after 513 days in circular external fixation. He had achieved soft tissue healing and completed a 55-mm bone transport at the time of his amputation. The remaining 4 patients had achieved osseous and soft tissue healing with subsequent removal of their circular external fixation at an average of 314 days (range 246–379 days). All 4 of these patients are able to ambulate and are currently participating in an aggressive rehabilitation pathway and have been fit with a customized orthotic.[29,30]

DISCUSSION

Large soft tissue defects of the leg, especially distal wounds and those whose size precludes rotational muscle coverage, have traditionally been covered with free tissue transfer from larger muscles such as the latissimus dorsi or rectus abdominis. Even in the setting of smaller wounds amenable to rotational coverage, some authors have suggested that free tissue transfer be performed for type III-B open tibia fractures associated with severe bony involvement (OTA type C), citing increased wound complication rates with rotational coverage.[31] More recently, this philosophy has been challenged, however. In a cohort of more than 200 open combat-related tibia fractures, Burns et al[32] demonstrated higher amputation and reoperation rates in those patients managed with free tissue transfer compared with rotational flap coverage, even in fractures with severe bony injury. Based on this work, and additional studies citing the benefits of early wound coverage,[33–35] we began using acute shortening with angulation to obtain primary wound closure or create a wound environment amenable to skin grafting alone.[21,22] The GEM flap is a stepwise progression of this technique for wounds too large for a rotational flap or shortening with angulation alone. The 20% amputation rate in this series closely matches that of Stinner et al who demonstrated a 15% delayed amputation rate after reconstructive attempts in their analysis of 950 combat-related amputations.[34] The presented amputation rate is also a substantial improvement compared with 64% amputation rate of Burns et al after free flap coverage of combat-related type III-B open tibia fractures.[32]

The introduction of the Taylor Spatial Frame and its hexapodal software-driven deformity correction capabilities has dramatically expanded the armamentarium of the limb salvage surgeon, offering the ability to use Ilizarov techniques to regenerate lost bone and soft tissue through distraction histiogenesis while also providing a platform for easier deformity correction. Nho et al[21] have previously described the technique of shortening and angulation to obtain primary soft tissue closure of the leg. After wound healing, a gradual deformity correction can be obtained to restore limb length, alignment, and rotation. The technique avoids the need for rotational flap or free tissue transfer and may even obviate the need for skin grafting over fascia and muscle if the wound can be completely closed.

The underlying biological mechanisms responsible for the ability to extend muscle flaps to larger soft tissue defects have been previously described.[37–41] In experimental models, muscle distraction causes an increase in sarcomere number and muscle weight, in addition to an increase in the number of proliferating satellite (myogenic precursor) cells. Muscle lengthening produces microlesions, resulting in the activation of these satellite cells, which subsequently undergo proliferation and fusion to the damaged area, ultimately resulting in an increase in sarcomere number and contributing to an overall increase in muscle length.[40,41] Although empiric determinations of muscle tension are difficult, previous authors have demonstrated dramatic increases in muscle growth under the tension-stress effect.[42]

The GEM flap technique described herein is an extension of the acute deformation concept whereby shortening and angulation is combined with rotational coverage to avoid free tissue transfer in large defects not amenable to deformation alone. To the author's knowledge, the use of distraction histiogenesis to extend the use of rotational flaps to larger wounds has not previously been described. We have demonstrated in a small series of patients that the technique is safe and effective for large areas of composite bone and soft tissue loss and, most importantly, does not compromise the integrity of the flap by stretching or kinking the vascular pedicle. Like other Ilizarov techniques, it requires a working knowledge of distraction osteogenesis principles and the safe zone for thin wire and half pin placement about the leg. Its most powerful use comes in situations where free tissue transfer for massive soft tissue defects could compromise lower extremity perfusion (single vessel limb) or is not chosen for other reasons (eg, lack of microvascular surgeon, patient preference, etc.). Under these circumstances, it affords the surgeon another technical tool to avoid unnecessary amputation and work toward limb salvage.

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